Characteristics of The 2MASS Prototype Survey

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1. Abstract

The 2 Micron All Sky Survey (2MASS) will catalog over 100,000,000 individual objects, the vast majority of which will be stars of spectral type K and later. For many projects it will be important to develop techniques to identify interesting objects within this dataset. The combination of near-IR and visible light observations will be a powerful tool for finding objects from brown dwarfs to dust-enshrouded quasars. This paper describes prototype hardware and software systems used as part of the preparation for 2MASS survey. Three years of observations with prototype systems have produced a database of more than 1 million objects. A companion paper describes the comparison of these data with optical plate material and visible spectroscopic observations resulting in the discovery of a quasar with a redshift of 0.147.

Subject headings: large-scale structure of universe — galaxies: general — Galaxy: structure — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — Infrared radiation

2. Introduction

The goal of the 2 Micron All Sky Survey (2MASS) is to map the entire sky at three near-infrared wavelengths (Kleinmann *et al.* 1994; Skrutskie *et al.* 1997) with 10σ sensitivity limits of 15.8, 15.1, and 14.3 mag at wavelengths of 1.25 (J), 1.65 (H) and 2.2 (K_s) μm (Table 1). As part of this effort, a prototype camera incorporating a single NICMOS-3 array was developed for use on the Kitt Peak 1.3 m telescope. The telescope and camera are used in a novel fashion for rapid acquisition of data with high photometric precision. A prototype data processing pipeline was developed at the Infrared Processing and Analysis Center (IPAC) with the goal of making a highly complete and reliable set of catalogs and images. The prototyping exercise has been extremely successful with many technical lessons carried over into the construction of the survey hardware (telescopes and 3-channel cameras) and software. The survey goals (Table 1) have been achieved with a single band camera and there is every expectation that the same performance, or better, will be achieved with the survey hardware.

Much of the data obtained with the prototype camera data is of good quality and has been processed into a database consisting of more than 1 million individual point sources over 160 sq. deg. of sky. We have begun to analyze these sources to understand how the final database of >100,000,000 2MASS objects can be used to advance a number of scientific goals, including galactic structure, the distribution of galaxies in the local Universe, and the search for rare objects such as brown dwarfs and extremely red extragalactic sources. This paper describes the systems (camera and software) used to generate these prototype data. Differences between the prototype and final systems will be briefly noted. This paper concerns results for point sources only.

A companion paper describes the outcome of the comparison of 2MASS data with optical plate material and some optical spectroscopic observations. This follow-up activity led to the discovery of a quasar at $z = 0.15$ (Beichman *et al.* 1998). A related paper using the 2MASS prototype data describes the discovery of a star of very low mass (Kirkpatrick *et al.* 1996).

3. Prototype Camera Data 1992–1994

Table 2 and Figure 1 summarize the protocamera raw database for data obtained on observing runs between 1992 to 1994. The resultant point source files contain 1,180,101 objects having a measurement with SNR> 5 in at least one band. While most of the sky was scanned only at K_s, there are over 162,000 objects seen in all three bands. While a variety of flaws in the early prototype camera and processing software (1992-1993) render the quality and completeness of these data less than the survey requirements, their overall reliability and accuracy is adequate for many investigations, especially in high-latitude fields, $|b| > 20°$, where the effects of confusion are small. The total survey area for the resultant database is 160 sq. deg (~0.4% of the sky); the distribution on the sky is shown in Figure 1. The quality of the data from the modified prototype camera (data obtained April 1994) meets the survey goals in all respects. A separate observing run in May 1995 contains as much high quality photometric data as all previous prototype camera runs and includes three-color coverage for nearly every field. The May 1995 data were processed with the algorithms described herein, but the results of those observations will be described elsewhere.

4. The 2MASS Observing System

2MASS uses a novel observing technique called *Freeze-Frame Scanning* to maximize data acquisition efficiency while providing high photometric and positional accuracy. More than 90% of the time during a scan is spent integrating. This section describes both the observing technique and the single channel prototype camera used to develop this procedure.

4.1. The Prototype Camera

All observations were made at the Cassegrain focus of the Kitt Peak 1.3 m telescope. In the original version of the proto-camera, an ZnSe refracting lens system re-imaged the sky onto a single 256 × 256 NICMOS-3 array. Each 40 μm pixel subtended 2.3″ on the sky for a total field of 588.8″ square. Chromatic aberrations resulted in variable image quality over the field with particularly poor performance in the J-band. The typical Full-Width-Half-Maximum (FWHM) of the Point Spread Function (PSF) for the 1992-1993 data was $\sim$4″. The camera optics were subsequently redesigned to give 2.0″ pixels with a PSF$<$ 2 ″ across the entire 1.25-2.2 μm band and across the resultant 512″ field. The redesigned camera (Skrutskie *et al.* 1997) was used in 1994 and thereafter. The redesigned camera also showed a greatly decreased number of artifacts due to ghosts or internal glints. The successful operation of the redesigned optics led to adoption of this design for the three-channel cameras being built for the 2MASS survey.

Two NICMOS-3 chips were used in the course of these prototype observations. Both had read noises in the range of 50 e^- enabling background-limited observations in all three bands in 1.3-1.5 sec integrations. One array had a bad column running through the center of the array. For one observing run, this bad column was aligned with the scan direction resulting in a $\pm$7″ gap in the middle of the field. In subsequent observing runs, the camera was rotated so that this bad column introduced at most one missing sample out of the 5 (in 1992-93) or 6 (1994) possible samples for each observation of a source (see §4.4).

The filter passbands used in the prototype camera correspond to the standard astronomical J and H passbands and a modified K passband denoted K_s (2.00-2.32 μm) designed to minimize the effects of telescope and atmospheric backgrounds.

4.2. The Freeze-Frame Scanning Technique

The technique developed for scanning the sky utilizes a combination of steady telescope motion in one direction (North or South) that is combined with an opposite motion of the telescope's chopping secondary. The net result of these motions is that the sky is frozen in the focal plane for a specified integration time. At the end of the integration time, the secondary mirror flies back to its starting position to freeze a new piece of sky, shifted by about 20% of the field of view of the array. The array reset occurs during this fly-back interval. The NICMOS array is read out at the beginning ($Read_1$) and at the end ($Read_2$) of the period that the field of view is frozen to give an integration time denoted τ_{R2-R1}. After the data have been read out, the chopping secondary is reset so that the sky is offset in the focal plane by $\sim 1/NSAMP$ of the height of the focal plane in the scan direction (Figure 2). The observational sequence continues until the telescope has scanned ~6° or roughly 250 individual frames. By this technique, every piece of sky (except for small portions at the beginning and end of each scan which are rejected) is sampled $NSAMP$ times. In 1992-93 NSAMP was set at 5 samples. In 1994 NSAMP was set at 6 samples, which is the value adopted for the 2MASS survey.

An important part of the observing sequence is that as soon as the sky is frozen on the array, the NICMOS array is reset and then read out a short time later to provide $Read_1$. This short integration time, denoted $\tau_{R1} \sim 50$ msec, allows the accurate measurement of bright sources that would otherwise saturate the NICMOS array and results in an increase in dynamic range given by the ratio of integration times, ~3.2 mag.

There are a number of strengths of the freeze-frame technique that have led to its adoption for 2MASS.

1) The telescope motion is continuous so that only the time necessary to stabilize the secondary motion (~20 msec) is lost. Scanning is highly efficient compared with a *point and shoot* method of stepping the entire telescope a fraction of the field of view between exposures. The areal scan rate, $\dot{\Omega}$, is $\sim$ 12 sq. dg. hr^{-1}. With only a short time required to offset the telescope in right ascension after each scan, the demonstrated efficiency of *freeze frame observing* is very high.

2) Using the chopping secondary to move the image minimizes the number of warm optical elements in the beam, thereby minimizing both the background and its variation during data acquisition scans. The data verify this expectation with variations in the background at K_s dominated by long-term drifts in the atmospheric airglow and thermal emission from the telescope.

3) An important aspect of Freeze-Frame scanning is that the technique mitigates against the inherent *undersampling* of the 2MASS data. In nights of good seeing, the 2″ pixels of the camera do not properly sample the inherent PSF through the atmosphere and telescope. Undersampling can be particularly deleterious in the presence of bad pixels since flux from a star can be irretrievably lost. The freeze-frame technique results in sources being measured at different positions on the array, thereby minimizing the effects of dead pixels and pixel responsivity errors. Since the array is rotated by a fraction of a degree relative to the scan angle, multiple samples are obtained at different relative pixel locations in both the x and y directions. The effects of dead pixels are further reduced by treating dead pixels carefully in the data processing (§4.3.4). The nominal sampling results in stellar images being offset by ~2/NSAMP of a pixel (*modulo* one pixel) in-scan and by ~1/NSAMP of a pixel cross-scan (Figure 2). These parameters were used in data taken in 1994 and thereafter. The combination of the NSAMP frames are rebinned to a ~1″ grid to yield images with improved spatial resolution relative to a single camera frame.

4.3. The Data Reduction Technique

2MASS will produce a large volume of data nightly, ~500 kbytes s^{-1} or ~15 Gbytes per night per telescope equipped with a three-channel camera. A highly automated data processing system is needed to keep up with data from two telescopes (Mt. Hopkins and CTIO). A prototype data analysis system was created at IPAC to develop an understanding of the necessary steps in creating the final pipeline. The main system components for the processing of point sources are outlined below. The galaxy processing steps are outlined elsewhere (Schneider *et al.* 1997).

4.3.1. Input processing

Straightforward techniques are used to read tapes from the observatory and to log header information for bookkeeping purposes.

4.3.2. Dark Frame generation and Flat Field Generation

For each observing run a dark frame was generated from sequences of exposures made with a cold shutter in place over the array. NICMOS arrays are susceptible to electronically generated gradients ("shading") in each quadrant. This shading depends on the photon flux level within a frame and thus differs between dark and sky frames. This difference results in flat-fielding errors in the declination direction in each quadrant at the few percent level. These errors have a highly repeatable, fixed pattern that averages out in the freeze-frame acquisition mode. Pixels with aberrant dark current values were masked as dead at this stage.

Within each scan, sequences of $\sim$ 25 frames at the beginning, middle, and end of a scan were median-averaged to form an estimate of the response of the array to a uniform background. This flat-field response was used to correct the pixel responsivity variations in the array. Typically 2-4 flat field frames were determined for each 6° scan. A linear interpolation in time was used to derive the flat field appropriate to correct a particular frame. Pixels with aberrant responsivity values were masked as dead at this stage.

An alternative technique of using images of the twilight sky at different brightness levels was used for some of the data processing. This technique was ultimately determined to be superior than the median-flat technique for deriving the pixel-responsivity map for the array and was used after 1994.

Every frame in a scan, including both the $Read_1$ and the $Read_2$ frames, was corrected for dark current and gain variations using data generated in the preceding steps.

4.3.3. Frame-to-Frame Offset determination

A preliminary extraction is made of sources in each camera frame to tie all the frames together with sources observed in common on $NSAMP$ different frames.

4.3.4. Source Detection and Parameter Estimation

A special algorithm, called KAMPHOT, was developed to deal with the unique aspects of the 2MASS data. It is particularly important to deal with the problem of dead pixels properly to avoid flux estimation errors in undersampled data. KAMPHOT operates in two steps: detection followed by characterization through Point Spread Function (PSF) fitting.

The detection step uses a matched filter derived from the PSF to search the *average* of $NSAMP$ frames, aligned according to the frame-to-frame offsets determined above, for pixels in the matched filter output brighter than a threshold, $\sim 4\sigma$, above the noise.

Parameter estimation proceeds by first isolating all pixels in the individual $NSAMP$ frames that contain information relevant to a source. The individual pixels from the various frames are aligned according to the offsets and are then fitted to an assumed PSF. The best fit to the data is derived through a χ^2 minimization and results in a position and amplitude of the source.

It is important to note that when dealing with *undersampled data*, the KAMPHOT technique of using all the frames separately is superior to carrying out photometry on the average of all the individual frames. The averaged image has lost all information on the location of dead pixels. Since the location of a source within a dead pixel cannot be known, the flux for a source contaminated by one or more dead pixels would be biased by $\sim 5-10\%$, if the information is obtained solely from the average image. This bias would affect $\sim NSAMP \times \frac{\# badpixels}{256^2} \times (\# badpixels/PSF)$, or roughly 1-5% of all sources for typical array yields. This effect is eliminated by using data in all the frames simultaneously.

Another source of photometric uncertainty is to an imperfectly determined PSF. Because of significant optical aberrations in the data used for the observations in 1992-93, seeing was not an important source of time-variable PSFs. Far more important than seeing were spatial variations across the array and temporal variations due to changing telescope focus. However, only one PSF was used for the processing of all 1992-3 data. A second set of PSFs were derived for the 1994 data obtained with the upgraded protocamera. For these data, a single PSF was adequate for sources over the entire field-of-view.

Corrections for the variable PSF were made by using a normalization technique with respect to aperture photometry results for bright sources. These normalization factors were established as a function of time and cross-scan position and were applied to all the PSF-fit photometry. The corrections were as large as 0.5 mag at the extreme edges of the focal plane or during periods of bad telescope focus. The residual error as determined by measurements of the same sources on different scans is estimated to be < 0.1 mag, and usually < 0.05 mag. Errors as large as 0.5 mag remain for a few sources ($\sim$0.1%). These corrections were necessary only for the early protocamera data. After 1992-93, a single PSF matched to the seeing but uniform across the focal plane was demonstrated to be adequate to meet all photometric requirements.

Measurements of bright sources were carried out in a simplified manner using the $Read_1$ data only. The average of the $Read_1$ frames was searched for sources whose position and brightness were then determined using aperture photometry. The $Read_1$ brightness scale was set using the $\sim$ 1 mag overlap between the $Read_1$ and unsaturated $Read_2 - Read_1$ source extractions.

4.3.5. Position Reconstruction

The in-scan and cross-scan positions of extracted sources were combined with rough knowledge of telescope pointing to find matches between 2MASS objects and the Hubble Guide Star Catalog (GSC; Lasker *et al.* 1988). The density of matched sources varied from 100 sq. deg.$^{-1}$ at the galactic pole to 10^3 sq. deg.$^{-1}$ close to the Galactic plane. The matched stars were used to establish the scan rate, orientation and other parameters. This information was used to interpolate the celestial positions of all 2MASS sources using a cubic spline. Data obtained in 1992-93 were corrected for cross-scan optical distortion.

Two components contribute to the positional errors. First are the uncertainties in the in-scan and cross-scan positions resulting from the PSF fitting. Multiple observations of the same region show that the repeatability of the positions is of order 0.25″ for sources with SNR>10. The second major source of error is related to the astrometric accuracy of the GSC itself. While the typical uncertainty of a GSC star is ~0.5″, GSC positions for objects near the boundaries of photographic plates used to derive the GSC have errors as large as 2-3″.

The real 2MASS survey will use a different approach for position reconstruction, relying solely on astrometric data from the Hipparcos-Tycho catalogs. In the new scheme, individual frames will be linked to one another via stars observed in the overlap region, and then the entire scan will be placed onto the sky using Tycho stars detected in the scan. Preliminary reductions of prototype data using the new technique has already demonstrated that the 0.5″ requirement will be met.

4.3.6. Photometric Calibration

Many observations of photometric standards were made as part of the prototype camera observations (Table 6). Photometric zero-points were applied to the data nightly using a standard extinction correction of (0.08,0.02,0.06) mag/airmass at (J,H,K_s). Given the large dispersion of photometric accuracy due to various PSF difficulties no effort was made to improve the calibration beyond the ∼0.05 mag level or to investigate color terms in the transformations to standard magnitude systems.

4.4. Clean-up Processing and Source Merging

A number of steps were taken to remove artifacts, merge sources, etc. from the source lists from individual scans. Some of these are unique to the prototype camera, while others will be incorporated as a routine part of the 2MASS survey pipeline.

4.4.1. Read-1 Merging

Sources in each scan brighter than some threshold had their (saturated) $Read_2$-$Read_1$ magnitudes replaced with $Read_1$ values. Sources in the $Read_2$-$Read_1$ list brighter than (J,H,K_s)=9 mag were matched with the $Read_1$ list with a match radius of 4″. For $Read_1$ matches between 7 and 9 mag, $Read_2$-$Read_1$ sources had only their magnitudes modified by adopting the $Read_1$ value. The $Read_2$-$Read_1$ position was better than that available from the short $Read_1$ exposures. Sources with $Read_1$ magnitudes brighter than 7 mag were replaced completely by their $Read_1$ counterparts since measurements for very bright objects suffer from many problems. Some very bright sources were found only in the $Read_1$ lists.

4.4.2. Confusion Clean-up

The merged source list was sorted by magnitude and the vicinity of all sources was examined in descending magnitude order for confusion. All sources within the larger of 3″ or $R_{confusion} = 3.0 \times 10^{0.43*(9-mag)}{}''$ of the brighter source were deleted out to a maximum radius of 120″. This functional form was selected by reference to the radial profiles of saturated stars and to the density of spurious sources around bright stars. This step removed spurious sources found around the saturated peak of a source or along the diffraction pattern of the secondary mirror supports, etc. The exact coefficients for the rejection depended on details of scattering within the camera and telescope optics, the onset of detector saturation, and the seeing.

4.4.3. Persistence Clean-up

NICMOS III arrays have the property that individual pixels continue to generate charge for some time after being illuminated by a bright source. The charge can take up to 15 seconds or 8-10 read cycles to die away below the level of the noise. Since the telescope is scanning smoothly in declination, this "persistence" charge produces a trail of sources of ever-decreasing magnitude, spaced by the frame-to-frame separation following the bright source. The first persistence source is approximately 6 magnitudes fainter than the parent source. The effect is important for sources brighter than about $K_s \sim$ 9 mag.

The well-determined frame-to-frame offsets were used to predict the positions of persistence objects. For sources brighter than (J,H,K)=(9.5,9.0,8.5) up to 8 objects were searched for at spacings of $N = 1, 2...8$ times the frame-to-frame offsets relative to the parent source. All sources located within a radius of $\sim 2.0''$ of the predicted position were deleted. Although typically 0.5-1.0% of the sources in a scan might be due to persistence artifacts, the highly repeatable geometrical signature of the effect means that the excision of the artifacts is almost completely effective. The deleterious effect of the persistence removal is the loss of real stars that happen to fall onto a persistence artifact. It is only in the densest regions and for the brightest stars (for which one searches for numerous persistence echoes) that persistence removal has any appreciable effect on completeness.

4.4.4. Bad Column Removal

Data from October and December 1992 suffered from an intermittent bad column in the NICMOS array. Since the column was oriented in the scan direction, the bad column produced a "trench" of missing or corrupted data, particularly in $Read_1$ images. Even though this part of the array was masked out in the data processing, the positions and magnitudes of sources near the bad columns were often adversely affected. Sources with average cross-scan positions within ± 3.5 pixels of the bad column were deleted.

4.4.5. Ghost Removal

A ghost image of bright stars (i.e., a reflection off internal optical elements) appeared throughout the J-band data. During 1992 and 1993, the magnitude difference between the ghost and its parent star was $\sim$5.5 mag. In general, ghosts were extracted as separate, spurious sources if the parent star had a magnitude in the range $8 < J < 10$ mag. For fainter parent stars, the ghosts began to blend into the background, whereas for brighter parent stars, the ghost image was blended with the parent and so the ghost was not extracted as a separate source. The ghost's predicted position was calculated on a scan-by-scan basis for each bright star. Any extracted source falling within 3″ of this predicted position on the scan was expunged from the data. This step removed 1% of the sightings at J band. Ghosting was virtually eliminated with the revised camera design demonstrated in the 1994-1995 data.

4.4.6. Single Band Merging

Many sources were observed multiple times during 1992-1994 and some calibration fields observed as many as 68 times. All sightings for a particular source were combined into a single measurement as follows. A magnitude sorted list of objects was searched for matches in descending magnitude order. All objects within a radius of 3″ and within a magnitude window of 1 mag were combined into a single representation of the source; sources fainter than 1 mag of the seed were deleted as confused. The derived magnitude and position were obtained by a simple average of all sightings. At this point the source record loses all information of its time history. The position, magnitude, derived magnitude uncertainty (calculated using the sigma of the separate measurements if there were multiple sightings; otherwise, the KAMPHOT value), number of observations, and a χ^2 for the magnitudes based on the quoted uncertainties in each sighting were calculated. A minimum magnitude uncertainty of 0.02 mag was used for all sources.

Table 3 shows the statistics resulting from this confirmation process in the three bands. The positions are generally within 0.25″ and the magnitude uncertainties <0.1 mag. The magnitude uncertainty is for *all* sources and is dominated by the faintest ones. For the brighter sources the photometry is internally consistent to approximately 0.05 mag.

Figure 3 shows a typical histogram of the magnitude uncertainties for sources seen multiple times. Large uncertainties are possible in confused regions, e.g., the galactic plane, where false matches and confused parameter estimation are likely.

4.4.7. Multiple Band Merging

The last step in the process was to combine sightings from different bands. This process suffered greatly from the fact that there was no attempt to ensure multi-band coverage for most regions scanned. By far the largest number of sources are found at K_s, then at H, finally at J (Table 3). The band merging was carried out by merging magnitude-sorted lists of sources from the brightest downward. First the K_s and H sources were merged, then the resultant K_s-H lists were merged with the J data. All sources within $4''$ were combined. In case of confusion an attempt was made to take the closest source ($< 1.5''$) if that eliminated the confusion, otherwise the brightest source was taken. Other sources within $4''$ were deleted. Positions were obtained by calculating the noise-weighted average of the positions in the detected bands.

Because of the highly uneven wavelength coverage, no systematic attempt was made to find upper limits for unmatched bands. However, if a source in an empty band was found within $30''$ of the seed source, then a flag was set indicating that there might be coverage in that band in this area.

Sources had to have at least one high quality flux (Table 4) to be accepted into the final source list. Lower SNR detections were used to provide some information in the other bands. After band-merging was completed, a final clean-up pass was made to fix band-merging problems due to confusion. Sources with final positions closer than $3''$ were combined by taking, on a band-by-band basis, the measurement with the largest number of sightings as the correct representation of the source. This processing affected roughly 1,600 sources out of the total of 1 million objects. The distribution of the final source list by band combination is given in Table 5. The difference in number of the various band combinations is completely dominated by spotty band coverage in various regions and not by the actual colors of the objects.

5. Merging with Optical Data

The final prototype camera database was combined with source lists derived from POSS-I plates. Specifically, if there was a POSS-I source within 3″ of a 2MASS source, R and/or B magnitudes from the Automated Plate Measurement (APM) project (Evans and Irwin (1995)) are reported. There are three caveats about the optical data. First, some regions surveyed by 2MASS were not digitized by the APM. In these areas — with $|b| \lesssim 20°$ or $\delta \lesssim -2°$ — no B and R magnitudes are available. Second, the time baseline between the 2MASS data and the POSS-I APM scans is ~40 years, so proper motion objects moving more than ~0.08″ yr^{-1} will not be matched. Third, the APM often misses, or quotes as a single source, double objects separated by less than ~5–20″ whereas 2MASS correctly splits most of these objects. In these cases, one or both 2MASS sources will not have a reported B or R magnitude because the centroid of the APM blend falls outside the 3″ matching radius. The number of sources with and without APM magnitudes, in the region with APM coverage, is given in Table 5. It should be noted that 2MASS sources without identifications within 4″ may still have obvious optical counterparts due to effects of proper motion. Comparing 2MASS with older epoch plate material is an excellent way of identifying nearby, low mass stars (Kirkpatrick, Beichman, and Skrutskie, 1996).

5.1. Caveats and Disclaimers

The early 2MASS data described here are not wholly representative of the anticipated quality of the final survey. The hardware and software were all prototypes designed to reveal problems that would need to be resolved to carry out a survey that would meet the project goals. With improved optics in the prototype camera, and with evolving algorithms in the prototype pipeline, analysis of the data taken in late 1994 and May 1995 has shown that 2MASS will meet or exceed all its goals.

6. Analysis of Positions and Magnitudes

Table 6 gives the final 1992-1994 2MASS magnitudes for the photometric standard stars contained within the database. The differences between the 2MASS and standard magnitudes are shown graphically in Figure 4. With the exception of the J value for G 77-31 (which suffered from confusion), the magnitudes agree to within <0.1 mag. The average difference between the adopted magnitude values for the 20-25 stars and the values extracted from the database for those stars is less than 0.01 mag with a dispersion, $\sigma_{pop} \sim 5\%$.

Figure 5 shows the total (RA and Dec) positional differences in arcseconds between the 2MASS positions of PPM stars and the 2000-equinox, 1993-epoch positions of the same stars derived from information in the PPM Catalog. Total positional uncertainties for these stars are $\sigma = 0.8''$, but this uncertainty is overestimated because 2MASS positions for the bright PPM stars are typically derived from more uncertain $Read_1$ measurements.

7. Differences between Prototype and 2MASS Survey

The prototyping exercise was extremely valuable in learning how to modify survey hardware, survey strategy, and data processing algorithms to ensure meeting all the Level 1 specifications for the 2MASS survey. Most changes suggested by the prototyping have already been validated with modifications to the camera or processing pipeline. The major changes in the systems developed on the basis of this prototyping are described below. A detailed description of the 2MASS survey pipeline is given in Cutri (1997).

7.1. Hardware

Some of the hardware changes suggested by the prototyping activity included:

- The redesign of the prototype camera concentrated on making a uniform, achromatic point spread function across the focal plane, and on eliminating internal ghosts and reflections. The redesigned camera was operated in April, 1994, and May, 1995, and demonstrated excellent performance in these areas. The optical design of the redesigned camera is identical to the design adopted for each arm of the final three-channel survey cameras. Laboratory tests of the first three-channel camera show its optical quality is identical to that of the redesigned prototype system.
- The initial prototype camera had $2.3''$ pixels. Analysis of the ability to distinguish between stars and galaxies in the 1992-1994 data led to adopting $2.0''$ pixels for the redesigned camera and for the survey as a whole.
- The drifts in telescope focus evident at the Kitt Peak 1.3 m telescope demonstrated the importance of an athermal telescope design. This feature is a basic requirement of the two identical telescopes being built for the 2MASS project.

- The difficulty in locating the starting point of Kitt Peak scans in crowded fields lead to a requirement on $< 10''$ absolute pointing of the 2MASS telescopes.

7.2. Software

Running actual data through a prototype pipeline well in advance of the start of operations proved to be of enormous benefit to the software development. Many features of the software were modified in light of the prototyping experience. A few of the key differences between the steps outlined above and what will be used for the survey processing include:

- Examination of the 2MASS data led to the conclusion that for the highest precision photometry, repeatability of $<2\%$, the use of dome or twilight flats offered a better determination of the pixel gain variation map than the median sky flat due to the "shading effect" common to NICMOS-III arrays. The final 2MASS pipeline will use this alternative approach.

- The large number of point source detections available with the three channel survey camera, plus the availability of the Hipparcos Tycho catalog, have led to a completely revised position reconstruction scheme based on rigidly knitting together the individual camera frames using stars in the overlap regions and tying these frames to the sky using Tycho stars.

- The band-merging algorithms for the survey will be completely new compared with the simple algorithms employed for these data. The fact that the three bands will be obtained simultaneously in the survey enables band-merging and the derivation of upper limits with little possibility of confusion.

- Data from April 1994, and May, 1995, obtained with the improved camera quality of the redesigned camera highlighted the obvious importance of tracking PSF variations due to seeing to enable accurate photometry ($\sim 2\%$). Techniques have been developed to carry out this tracking as rapidly as every 30 seconds.

8. Conclusions

The 2MASS prototyping activity has been a very fruitful source of information on how to optimize the hardware, software, and survey strategy for the 2MASS survey. The fundamental conclusion of this effort is that the ambitious technical and scientific goals of 2MASS can be achieved.

The prototyping activity has resulted in a large body of data on point sources, the vast majority of which are late type stars. The combination of near-IR and optical-IR colors can be used to identify interesting classes of objects, e.g. a quasar (Beichman *et al.* 1997) and very late type stars as described in Kirkpatrick *et al.* (1997).

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